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6. AUTHOR(S)

H. L. Roitblat, P. W. B. Moore, D. A. Helweg, P. E. Nachtigall

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
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Representation and Processing of Acoustic Information in a Biomimetic Neural Network

Herbert L. Roitblat,¹ Patrick W. B. Moore,² David A. Helweg,¹ & Paul E. Nachtigall²

¹University of Hawaii-Manoa, ²NRaD/NCCOSC

Abstract

The effectiveness of artificial neural network models, depends strongly on the way in which the information to be learned is presented to the network. Use of biologically relevant mechanisms is likely to yield effective synthetic systems as well as understanding the performance of biological systems. We developed a model of the dolphin cochlea and used this model to produce the representations used by a neural network to model the delayed matching-to-sample performance of a bottlenosed dolphin. The model yielded psychophysical functions and matching choice accuracy similar to those obtained from the dolphin.

1. Introduction

The deployment of robots and other artificial creatures or "animats" depends strongly on the development of adequate perceptual and conceptual mechanisms for perceiving and recognizing objects and for navigation. Artificial neural networks are uniquely suited for solving problems in pattern recognition, signal detection in noise, speech recognition and adaptive control, and are likely to play an important role in animat development. These networks also offer a useful computational technique for modeling and studying biological processes both because of their effectiveness in biologically important tasks and because their structure resembles natural biological information processing architectures. Complementarily, we can use the information gained from investigations of biological performance to guide the structural development of artificial systems that accomplish analogous tasks. We can, in a sense, "reverse engineer" computational models from successful biological systems to aid in understanding the biological system.

The effectiveness of artificial neural network models, depends, in large part, on the way in which the information to be learned is presented to the network. There are no well established rules to guide the selection of these representations. However, an obvious and plausible source for direction in this process, is to incorporate what is already known about the way in which the biological systems being modeled represent important information, that is, to identify the features of the environment that control the animal's behavior and to identify the means by which such information is represented. Construction of artificial systems that implement functions performed by biological systems can benefit from the same, or close to the same mechanisms, as those used by the biological system. Use of biologically relevant mechanisms, represented with increasing fidelity, is likely to help us produce increasingly effective synthetic systems and to help us to understand the performance of their biological counterparts. Models aid understanding and they facilitate applications.

2. Dolphin Hearing & Sonar

Dolphins provide an excellent paradigm for developing artificial neural network models of biological signal categorization. Their categorization performance has been well studied, so there is ample background and a well-developed methodology for investigating these capabilities. They provide a well-bounded problem and demonstrate the solution of that problem, thereby indicating that biological-sonar-based recognition of various kinds of targets is feasible. Dolphins are of immediate practical importance in that they can be trained to recognize practical signals from real objects and to perform important tasks with those objects. Finally, this laboratory has already begun the development of various kinds of models for the decision processes (Roitblat et al., 1990) and for the sensory processes (Au, 1980) that the dolphin uses in object

recognition, and have developed some preliminary neural network models (Moore et al., 1991; Roitblat et al., 1991).

In addition to excellent visual capabilities comparable to those seen in other terrestrial mammals, dolphins interrogate their environment by sending out clicks from their rounded forehead or melon. The clicks reflect from objects that are directly in front of the dolphin and return characteristic echoes, from which the dolphin can extract information about the location and many features of the object (Nachtigall, 1980). Because the dolphin must emit clicks in order to engage its biological sonar and because the clicks are separated in time from other clicks, each echo corresponds to a discrete packet of information. The quantal nature of dolphin echoes greatly simplifies the problems associated with modeling continuous information acquisition mechanisms.

The biological sonar capabilities of the bottlenose dolphin (*Tursiops truncatus*) far exceed those of any artificial systems at object detection, recognition and many other close-range (i.e., within about 100 m) tasks. Dolphin echolocation signals emerge as a series of ultrasonic clicks from the melon as a highly directional sound beam with 3 dB (half power) beam widths of approximately 10° in both the vertical and horizontal planes (Au, Moore, & Pawloski, 1986). Dolphin echolocation clicks are broadband, have peak energy at frequencies ranging from 40 to 130 kHz, and source levels of up to 220 dB re: 1 μ Pa or higher (Au, 1980; Moore & Pawloski, 1990). Bottlenose dolphins have excellent directional hearing (Au & Moore, 1984) and a wide range of frequency sensitivity, spanning over seven octaves. The dolphin is sensitive to frequencies seven to 10 times (four octaves) higher than can be detected by humans, and can detect frequencies as high as 150 kHz (Johnson, 1966). The animal is maximally sensitive to frequencies in the 40 - 80 kHz range (e.g., Johnson, 1967).

Both the dolphin's signal production and hearing are specifically adapted to the underwater acoustic environment. Although both bats and dolphins use echolocation, the characteristics of the medium in which their signals are emitted, the mechanisms by which the signals are produced, the type of signals and the neurological apparatus they use to process those signals differ substantially (Zook, Myron, Ilya, & Morgane, 1988; Zvorykin, 1959, 1963). Bat biosonar is adapted for use in air, whereas dolphin biosonar is adapted for use underwater. Bat biosonar signals are relatively long in duration (up to several ms), and contain both narrow band constant-frequency and FM-modulated components depending on the species (Bellwood, 1988; Fenton, 1988; Suthers, 1988). By contrast the dolphin echolocation signal is very broadband and extremely short (about 50 μ sec).

The anatomy of the dolphin ear also displays aquatic specialization. Cetacean cochleas correspond generally to the standard mammalian design, with certain specializations. The standard mammalian ear consists of a tympanic membrane, which is in contact with the atmosphere and is the typical means by which sounds are transduced from the environment into the hearing system. The tympanic membrane connects via a series of ossicles to the cochlea, which in most mammals is a spiral rather than snail-shaped structure. If the cochlea were to be unrolled, it would have a cone-like shape with the oval window occupying its base. Within, and running the length of the cochlea is the basilar membrane. Sounds enter the cochlea through the oval window and excite vibrations on the basilar membrane. Because of the shape and stiffness characteristics of the basilar membrane, different frequencies differentially excite standing waves at specific locations along the membrane (Bekesy, 1944; Fletcher, 1940; Helmholtz, 1863). The inner hair cells contact the basilar membrane and transduce the movement of the membrane into neural signals for processing by the brain (Hudspeth, 1985).

Species-specific anatomical characteristics of the ears of whales and dolphins relate to the echolocation signals they produce and to the particular habitat and feeding behavior these animals exploit (Ketten, 1992). Among the specializations seen in the cetacean ear are isolation of the bulla from the surrounding skull, fusion and enlargement of the ossicular chain, and specializations in the shape of the basilar membrane and osseous spiral laminae, which support it. The thickness and width of the dolphin basilar membrane, like that of other mammalian species, varies monotonically from the base to the apex. Highest frequencies are encoded in the thicker, narrower portions of the membrane near the base and progressively lower frequencies are represented toward the apex as the membrane thins and broadens (Ketten, 1984, 1992; Wever, 1971a, 1971b). The dimensions of the basilar membrane suggest that dolphin ears are capable of an exceptionally wide frequency response. This prediction is consistent with the audiometric data.

Hair cells are approximately evenly distributed along the membrane at the density of about 100 inner hair cells per mm (Ketten, 1992). The hair cells synapse on ganglion cells, whose axons form the auditory eighth nerve. Tursiops ears contain approximately 105,000 ganglion cells distributed about evenly along the 41.6 mm length of the basilar membrane (i.e., averaging about 2,526 ganglion cells per mm of membrane length). In comparison the human ear contains about 30,500 ganglion cells distributed along 31 mm of basilar membrane, for an average of about 984 ganglion cells per mm. Ganglion cell densities are higher in odontocetes than in any other mammal and the ratio of

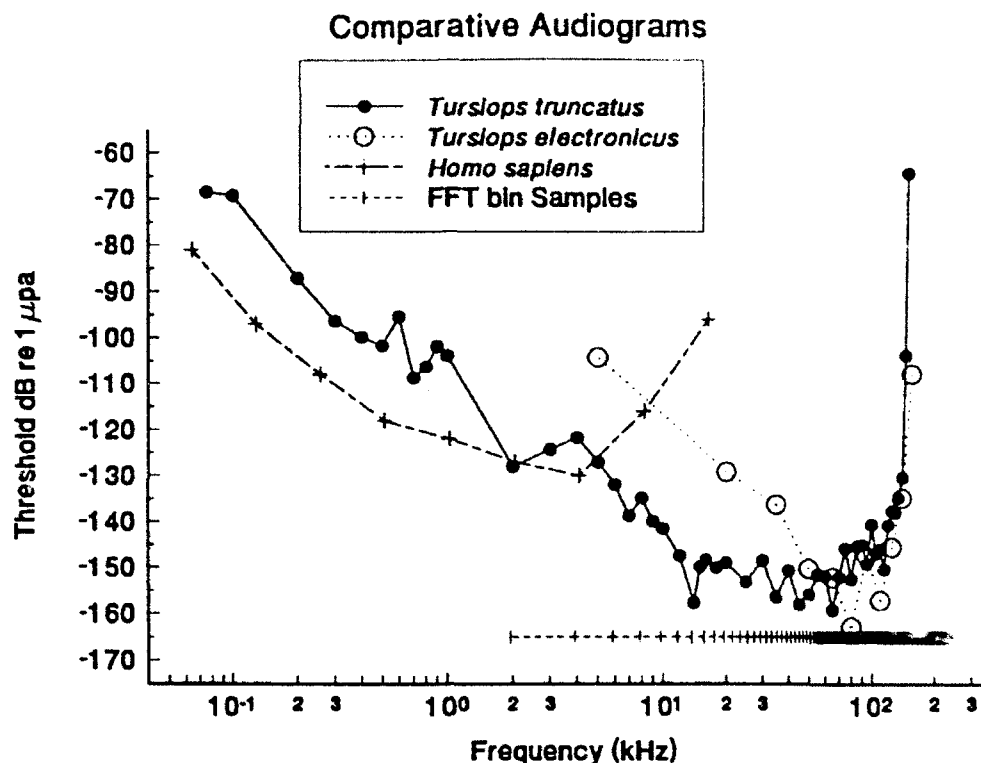


Figure 1. Dolphin, human, and simulated audiograms. FFT bin samples show the frequency resolution of the underlying spectrum on which the simulations were based.

ganglion cells to inner hair cells is about twice that in bats and about three times that in humans (Ketten & Wartzok, 1990).

Some properties of dolphin psychophysics are known. For example, dolphin frequency discrimination limens (ΔF) correspond approximately to Weber's Law: A stimulus must be increased by a constant proportion (ΔF) of its value to be "just noticeably different" (Weber, 1846). If the ΔF is the smallest discriminable difference, then $\Delta F/F = K$, a constant. Another way of stating this relationship is that the graph of $\log \Delta F$ versus $\log F$ is a straight line. At frequencies near 1 kHz, dolphins can discriminate frequencies differing by about 6 Hz; at 100 kHz, the smallest discriminable difference is approximately 800 Hz (Herman & Arbeit, 1972; Thompson & Herman, 1975). An exponential function fit to these data had an exponent of approximately 1.09, supporting the near linearity of this function.

Figure 1 shows the dolphin's audiogram (Johnson, 1967; Morozov, Akopian, Burdin, Donskov, Zaytseva, & Sokovykh, 1971). The dolphin's hearing is relatively insensitive at low frequencies and at very high frequencies above 150 kHz. Hearing tends to be most sensitive in the range between 40 and 80 kHz.

The frequency response of the basilar membrane and the distribution of inner hair cells and ganglion cells suggest that each ganglion cell functions as a band-pass frequency filter. Because of the cochlear characteristics described earlier, specific frequencies differentially excite the hair cells located in specific portions of the basilar membrane. Hence, each hair cell responds maximally to a limited range of frequencies according to how much those frequencies affect its location on the membrane. The ganglion cells combine activation from multiple hair cells distributed along a limited range on the membrane, and as a result, are differentially sensitive to a particular frequency band.

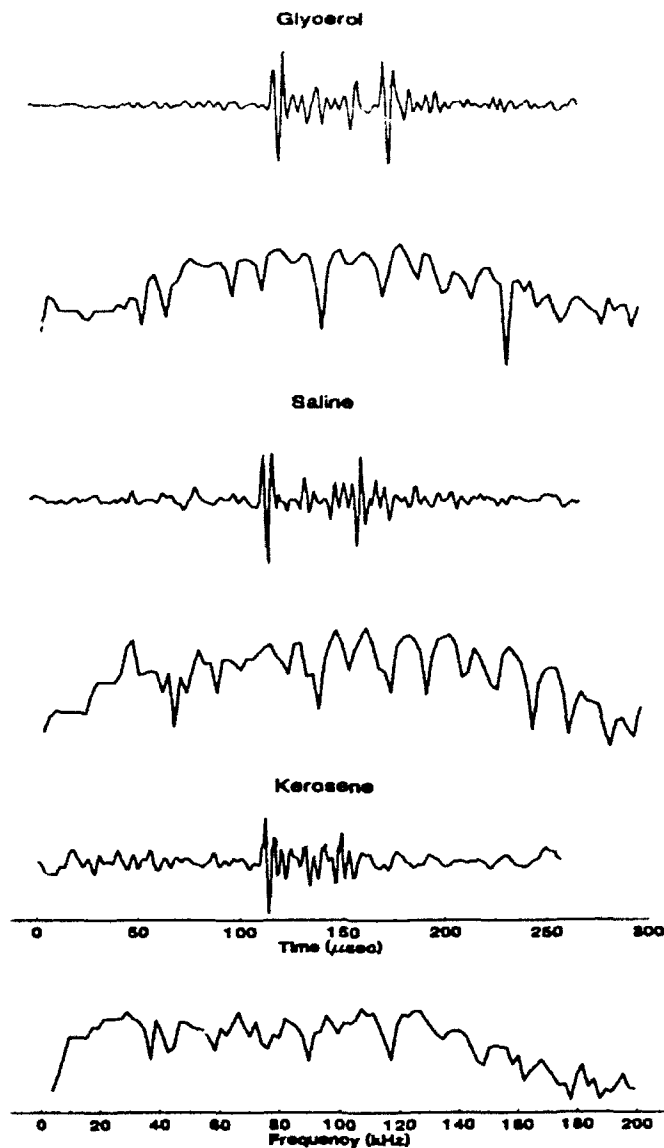


Figure 2. Example waveforms and spectra for the three target types used.

3. The Dolphin's Task

The dolphin performed a matching-to-sample task (see Roitblat et al., 1990 for details). Wearing soft removeable eyecups, the dolphin stationed under water and directed its echolocation clicks at a submerged target located in front of it. Following the dolphin's examination of this target, it was removed from the water and three other targets were placed in the water. The dolphin then echolocated on these targets and selected the target that most resembled the sample. The identity of the sample varied randomly from trial to trial and the location of the matching alternative also varied randomly from trial to trial, so the dolphin had to identify and remember the sample in order to correctly choose the matching comparison target.

We captured and digitized the dolphin's outgoing clicks and returning echoes that were directed at and reflected from the sample and the center comparison target. Clicks were obtained using a B&K 8103 hydrophone placed in the path between the dolphin and the center targets and echoes were obtained using a custom-built hydrophone placed next to dolphin. Signals were digitized at 500 kHz using an RC-Electronics A/D converter and custom-written software.

The stimuli used for the matching task were fuel bottles containing different materials—glycerol, physiological saline, and kerosene. All stimuli were identical in their outer form, differing only in their internal constituents. Example echo waveforms and spectra are

Filter Shapes

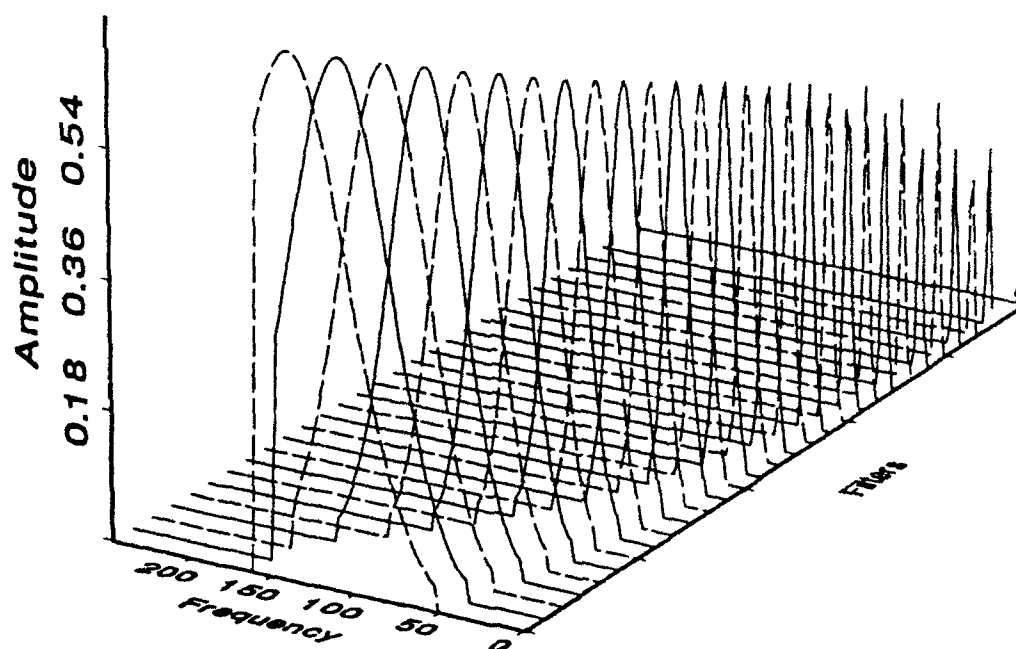


Figure 3. The filters used in the cochlear model.

shown in Figure 2. These stimuli were apparently very difficult to discriminate because the dolphin's choice accuracy was only 50%. Chance accuracy with three alternatives is 33%.

4. Model

We used the known facts about the dolphin ear and hearing to construct a computational model of the dolphin's ear that could be used to create principled inputs for our neural net model of the dolphin's decision processes. In developing any model, one must necessarily make simplifying assumptions. Some of these assumptions are dictated by computational constraints (e.g., the capacity of the computer's memory and time to perform the computations), some are dictated by other physical or electronic constraints.

Our model also includes a further constraint in that we wanted to be able to compare the performance of the model with that of previous models we developed for similar tasks, and we wanted to compare the model to the dolphin's performance.

Our basic data for input to the network consist of digitized 256-point waveforms, sampled at 500 kHz and transformed via an FFT to a 128 bin spectrum. Each bin represents the energy in an approximately 1.95 kHz wide band. Because the hearing of the dolphin falls off so sharply between 140 and 150 kHz we selected the first 85 bins for further processing. For computational reasons and in order to compare the present model to previous models, we needed a 30 bin vector to summarize the relevant frequency information. In previous investigations we had

averaged pairs of adjacent frequency bins between 31 and 150 kHz. All frequencies in this earlier model were represented equally--each bin represented a constant bandwidth. The evidence described above, however, suggests that in the ear, bandwidth varies with the frequency being measured. Lower frequencies are represented with narrower band "channels" than higher frequencies. The number of inner hair cells and ganglion cells in the dolphin ear is approximately constant over the length of the basilar membrane suggesting that each unit of length contributes about equally to representation of the signal. The range of frequencies represented by each segment of basilar membrane, however, is not constant. Near the base, each unit of basilar membrane length represents a broader range of high frequencies relative to the narrow range of lower frequencies represented near the apex.

In the present model we sought to generate the representational vector to correspond to known features of dolphin ears. Many of the parameters were selected on the basis of rough estimates, and the resolution of the model was fairly crude, nevertheless, such exercises are likely to be valuable in the long run in the development of effective biomimetic mechanisms.

The sensitivity of the ear was represented as a bank of 30 bandpass filters. Each filter had a Gaussian shape, meaning that it was most sensitive to its center frequency and had diminished sensitivity with increasing distance from the center. The center frequency of each of the 30 filters was selected according to Eq. 1:

$$\text{CenterFreq} = 160 \times \text{EXP}(-.1392 \times (i)) \quad (1)$$

in which i ranged from 1 to 30. This equation (Ketten, 1992, personal communication) is an estimate derived from the stiffness and size of the basilar membrane. According to this equation, the filters are approximately equally spaced along the length of the basilar membrane.

Each of the filters is characterized by its width as well as its center frequency. Bandwidth also varied as a function of the filters location on the basilar membrane as in Eq. 2:

$$\sigma = 40 \times 0.00201 \times (\text{CenterFreq}^{1.093}) \times \text{stepsize} \quad (2)$$

Stepsize is a constant corresponding to the bandwidth of the FFT bin (1.953125 kHz) in the underlying original FFT spectral distribution. This bandwidth is determined by the number of points sampled in the original signal and the

sampling rate. The total sensitivity of each filter was set according to Eq. 3:

$$\text{sensitivity} = (\sigma \times 2)^{0.139} \quad (3)$$

The rationale for Eq. 3 is that the spacing of inner hair cells and ganglion cells is about constant over the length of the basilar membrane, so the number of cells that are likely to contribute to the filter should be inversely proportional to the spacing between filters (Eq. 1). Filters that are spaced farther apart are expected, in other words, to receive inputs from a wider range of inner hair cells than filters that are spaced closer together.

The sensitivity of each filter was set to be proportional the height of the Gaussian distribution at the corresponding frequency. Figure 3 shows the resulting filters.

In producing the 30-element vector representing the eighth-nerve response of the simulated ear, the power in each bin of the underlying FFT distribution was multiplied by the height of the Gaussian distribution for that filter at that frequency and added to the output of that filter. Notice that the bins are arithmetically symmetrical. On a log scale, they would appear to cut-off more sharply at higher than at lower frequencies relative to each filter's center frequency.

5. Results

A simulated audiogram was obtained by comparing the response of the simulated ear when confronted with noise only versus when the system was confronted with a signal of a particular frequency in addition to the noise. Each simulated trial consisted of two parts. During the first part of the trial each frequency bin was set to a small random value. These values were then fed to the bank of filters (the matrix product of the noise vector and matrix of filter vectors was computed resulting in a 30-element vector). A new noise vector was then specified and the bin corresponding to the tested frequency for that trial was incremented by a fixed value. This vector was also fed to the bank of filters, also resulting in a 30-element vector. The discriminability of the two conditions was taken to be the Euclidean distance between the noise-only and signal+noise vectors. Each comparison was repeated 10,000 times. The resulting audiogram is also shown in Figure 1.

Frequency Limen

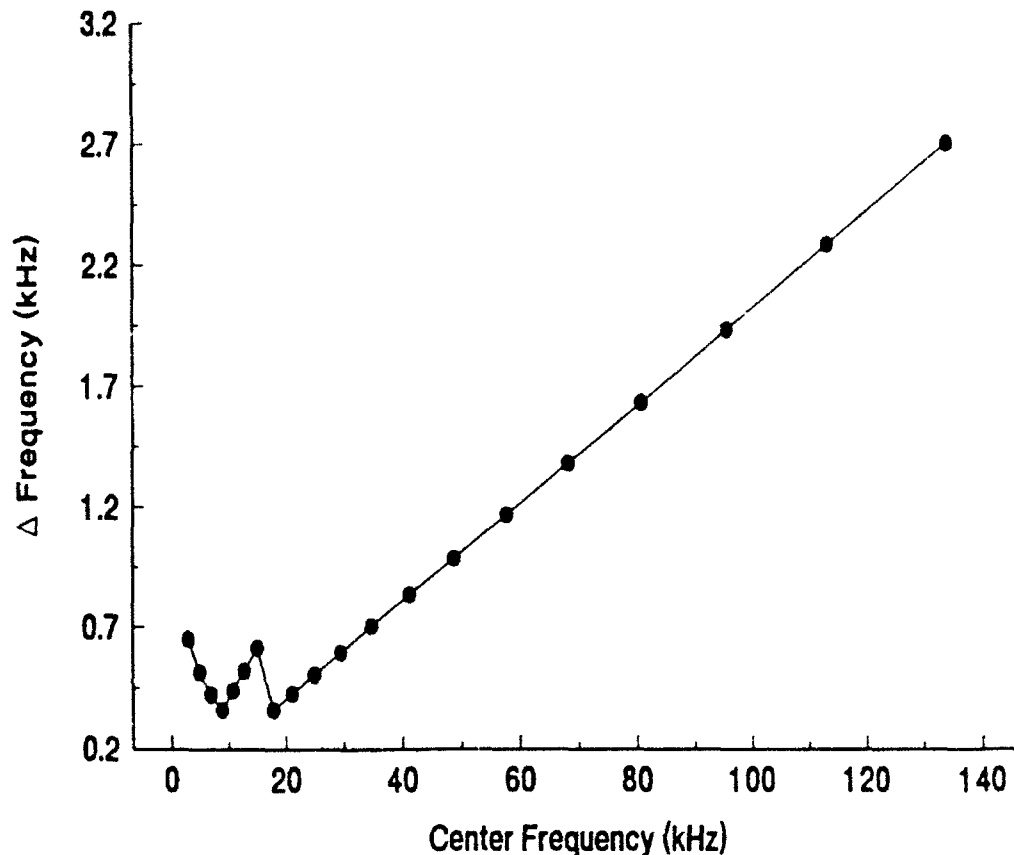


Figure 4. Smallest discriminable difference as a function of frequency.

In another simulated experiment we compared the difference limens predicted by the model with those observed in actual dolphins. These limens are shown in Figure 4. These limens correspond closely to the observed frequency limens, at least in the middle range of the dolphin's sensitivity. The crudeness of the underlying frequency analysis (i.e., the fact that our original representation uses 1.95 kHz wide bins) limits our ability to make fine discriminations at low frequencies.

Finally, we compared the performance of a neural network using the model as the input transducer to the neural network and comparing the network's performance to that of the dolphin on the difficult task of recognizing the substance inside the test bottles. That is, we used the

cochlear model as the "front end" of the network transforming the underlying FFT into a vector of 30 filtered amplitudes. We implemented the cochlear model as a preprocessor, but it could just as easily be implemented directly in the network by setting the strengths of the connections from the input layer proportional to the sensitivity of the filters.

For the neural network we used the integrator gateway model described earlier by Moore et al. (1991) and Roitblat et al. (1991). This network was designed to implement the underlying item-recognition processes thought to be used by dolphins in the delayed matching-to-sample task (Roitblat et al., 1990). It takes advantage of the observation that dolphins tend to emit a series of clicks to the same object and hence of the redundancy between successive echoes.

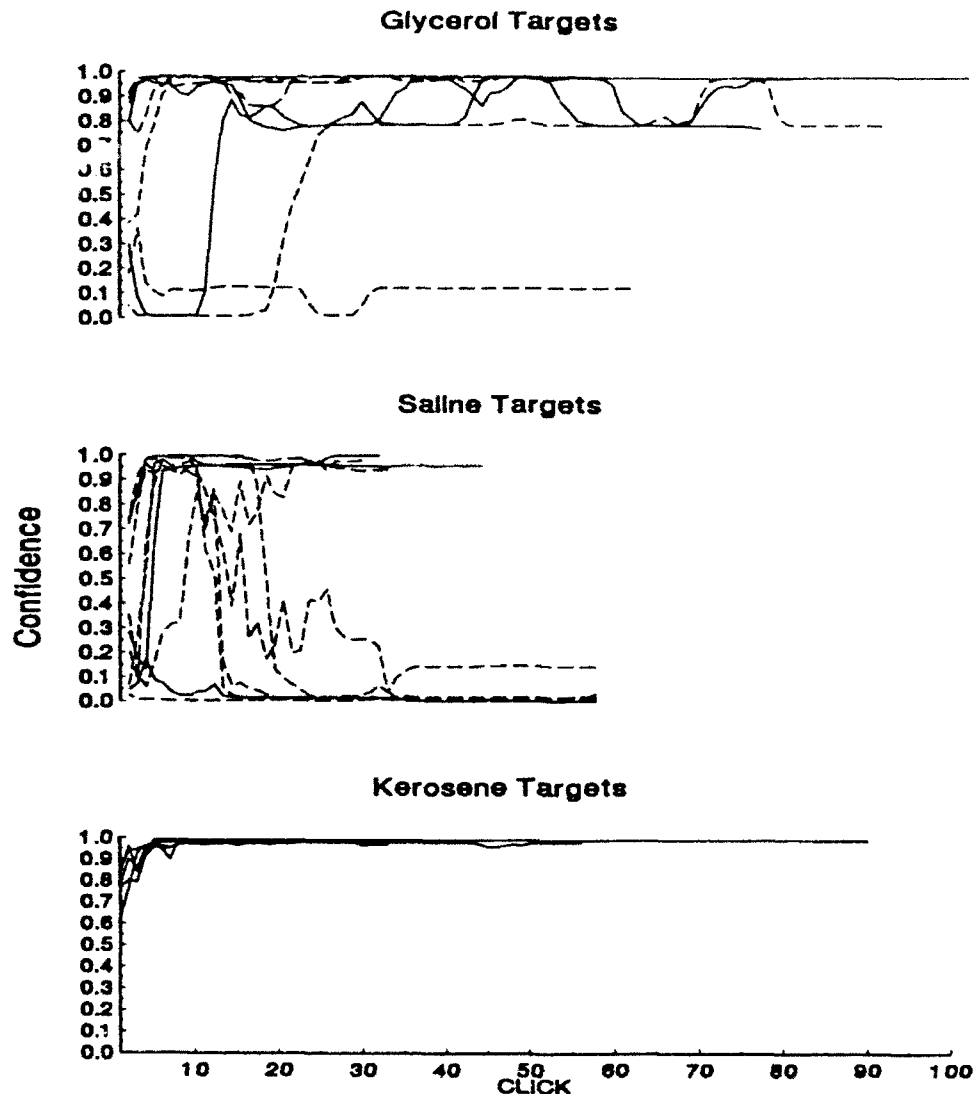


Figure 5. The confidence of a correct classification based on network output.

The network combines successive echoes in a train and computes a function similar to a running average.

The performance of this network is shown in the form of confidence ratios (see Moore et al., 1991; Roitblat et al. 1991). A confidence ratio of 1.0 indicates that the item was correctly and reliably identified by the network. A confidence ratio of 0.0 indicates that the network has misidentified the target as one of the alternative items. By convention we have chosen 0.96 as the dolphin's criterion of confidence. Ideally the dolphin should continue to emit clicks to a target until its confidence ratio reaches 0.96 and then stop clicking. In every experiment with this dolphin, however, he has continued to click beyond the point at which our network reaches this confidence criterion, suggesting either that the dolphin does not control his

echolocation click production on a click by click basis or we over estimate his ability to extract information from the signal.

Table 1 shows the number of clicks the network incorporating the cochlear model needed to reach a 0.96 confidence criterion and the number of clicks emitted by the dolphin on each trial. Figure 5 shows the course of the change in confidence over successive clicks.

6. Conclusions

The biomimetic approach holds significant promise for the development of artificial systems that mimic the functions performed by biological organisms. The present

Table 1. Integrator Gateway Network and Dolphin Decisions

Train #	Target	Decision	Number of Clicks	Dolphin Correct
1	Glycerol	Glycerol	3	-
2	Glycerol	Glycerol	3	+
3	Glycerol	Glycerol	6	-
4	Glycerol	Glycerol	2	-
5	Glycerol	Glycerol	12	-
6	Glycerol	Kerosene	23	-
7	Glycerol	Glycerol	3	+
8	Glycerol	Kerosene	3	+
9	Glycerol	Glycerol	3	-
10	Glycerol	Kerosene	13	-
1	Saline	Saline	3	+
2	Saline	Saline	3	-
3	Saline	Saline	3	-
4	Saline	Saline	19	+
5	Saline	Saline	21	-
6	Saline	Kerosene	7	+
7	Saline	Saline	4	-
8	Saline	Kerosene	6	-
9	Saline	Kerosene	17	-
10	Saline	Saline	5	-
1	Kerosene	Kerosene	4	+
2	Kerosene	Kerosene	8	+
3	Kerosene	Kerosene	4	+
4	Kerosene	Kerosene	6	+
5	Kerosene	Kerosene	2	-
6	Kerosene	Kerosene	2	+
7	Kerosene	Kerosene	17	+
8	Kerosene	Saline	9	-
9	Kerosene	Kerosene	2	-
10	Kerosene	Kerosene	5	+

Note: A train is a sequence of echolocation clicks to the same Target. The third column shows the decision that the network reached. Number of clicks is the number of clicks/echoes the network needed in order to reach the confidence criterion. The last column indicates whether the dolphin chose the correct (+) or incorrect target (-) on the indicated trial.

model incorporates what we know about dolphin cochlear and neural anatomy, psychophysics, and behavior, to develop an effective model of echolocation object recognition. Dolphins are capable of exquisite object detection and recognition performance. Incorporation of even a small portion of their capabilities in artificial systems would greatly enhance their effectiveness and capabilities.

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